Ongoing Wear Test of a XIPS© 25-cm Thruster Discharge Cathode

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The Xenon Ion Propulsion System (XIPS©) 25-cm thruster produced by L-3 Communications Electron Technologies, Inc. offers a number of potential benefits for planetary missions, including high efficiency and high Isp over a large power throttling range and availability from an active product line. The thruster is qualified for use on commercial communications satellites, which have requirements differing from those for typical planetary missions. In particular, deep space missions require longer service life over a broad range of throttling conditions. A XIPS© discharge cathode assembly is currently undergoing a long duration test to extend operating experience at the maximum power point and at throttled conditions unique to planetary mission applications. A total of 11080 hours have been accumulated at conditions corresponding to the full power engine operating point at 4.2 kWe and an intermediate power point at 2.76 kWe. Minor performance losses and cathode keeper erosion were observed at the full power point, but there were no changes in performance and negligible erosion at the intermediate power point.

I.   Introduction

At the time the NSTAR thruster was developed for planetary applications, there were no commercial ion thruster options in the required power range. In December 1999, however, Boeing launched the first of the 702 communications spacecraft with four Xenon Ion Propulsion System (XIPS©) 25-cm thrusters. There are currently 60 XIPS 25-cm thrusters operating on 15 geosynchronous communications satellites with no failures. A total of over 70000 hours have been accumulated in space. The XIPS 25-cm thrusters are designed to operate in two modes; a 4.5 kW "high power" mode with an Isp of 3500 s for orbit raising and a "low power" mode at 2.3 kW and an Isp of 3400 s for station-keeping, attitude control and momentum dumping. The high power and Isp capability of the XIPS thruster make it attractive for use on deep space missions. XIPS thrusters and PPUs are also available from an active product line which supports the commercial communications satellite customers, offering the potential for reduced cost and schedule risk. Recent mission and systems analyses comparing XIPS and NSTAR-based systems showed significant performance and cost benefits with XIPS for three candidate Discovery class missions–a Near Earth Asteroid Sample Return, a Comet Rendezvous, and a Main Belt Asteroid Rendezvous.[1]

There are three primary differences between the requirements for the use of XIPS thrusters in geosynchronous orbit and for deep space missions. First, the commercial communications satellite applications require only the low and high power modes, whereas planetary missions typically require continuous throttling over a broad range to accommodate changes in the available solar array power. Second, the lifetime requirements for planetary missions are more demanding. The commercial satellites applications require up to 1000 hours

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of operation in the high power mode and up to 8000 hours at low power, with a rated throughput of 130 kg of xenon. In contrast, planetary missions may require up to twice this life. Finally, there are minor differences in environmental qualification requirements that are not expected to require any design changes and can be resolved with a delta-qualification program. These differences are currently being addressed so that XIPS thrusters can be considered for NASA's deep space missions.[?] Throttling tests with the commercially-available XIPS thruster and PPU performed at L-3 ETI and the Jet Propulsion Laboratory (JPL) demonstrated that the thruster is capable of operating from 275 W to over 4.5 kW with only minor modifications to the PPU. The thrust, Isp and efficiency of the XIPS thruster met or exceeded those of the NSTAR thruster over the NSTAR throttling range of 500 W to 2.3 kW.[2]

A combination of analysis and testing is being employed to assess the xenon throughput capability (a measure of lifetime) of the XIPS thruster. The primary life-limiting components are the grids and the discharge cathode. The grid life is being assessed with state-of-the-art models of the ion optics, charge exchange processes and resulting ion sputtering that causes grid erosion.[3] These models have been benchmarked with data from the NSTAR program[4–6] and the XIPS qualification life test. Efforts to assess cathode lifetime include an ongoing wear test of a XIPS discharge cathode over a range of throttle levels, measurements of the electron emitter temperature in the cathode[8] as well as measurements and modeling of the internal and external plasmas and associated erosion.[7] The purpose of the wear test is to identify any previously unrecognized failure modes, characterize the known wearout processes and determine performance degradation due to wear. The results of the first two of three planned test segments at different operating points are summarized in this paper.

II.   The XIPS 25-cm Thruster

An exploded view and a photograph of the XIPS thruster are shown in Fig. (1). The 25-cm thruster consists of a cylindrical ring-cusp discharge chamber, a discharge cathode assembly, a three-grid ion accelerator system, a neutralizer cathode assembly and a plasma screen which surrounds the high voltage anode.[2,9] This engine was designed to perform the initial orbit-raising maneuver and all on-orbit propulsion functions for geosynchronous communications satellites. The first maneuver involves 500-1000 hours of operation at the high power point to boost the perigee of the elliptical orbit into which the spacecraft is launched up to the final circular geosynchronous orbit. On-orbit maneuvers require on average about 40 minutes of operation per day on each thruster at low power over a 15 year mission life.

Table 1. **Performance and operating parameters for the XIPS 25-cm thruster.**

Parameter	Low Power	High Power
Total Input Power (W)	2067	4215
Thrust (mN)	79	165
Specific Impulse (s)	3400	3500
Electrical Efficiency	0.87	0.87
Mass Utilization Efficiency	0.82	0.84
Beam Voltage (V)	1215	1215
Beam Current (A)	1.43	3.01
Discharge Current (A)	7.6	18.0

The thruster performance and operating parameters for each of the two modes are listed in Table (1). The thruster was qualified for the life required to meet the commercial applications in a wear test and with analyses of critical components.[10,11] The wear test included 2680 hours at the high power point in cycles consisting of 23 hours on and 1 hour off, and 13400 hours at low power with 13100 cycles consisting of 50 minutes on, 30 minutes off.[2]

In tests of the engine and PPU at L-3 and JPL, continuous throttling between 275 W and 4.5 kW was demonstrated.[2] This extended throttle range required discharge cathode currents of 3 to 18 A. Typical planetary missions are likely to require up to 3000 hours at the maximum power level, which exceeds the time accumulated at this point in the L-3 qualification life test. In addition, deep space missions will require extended operation at lower throttle levels for which there is very little wear test experience. These operating points are the main focus of the cathode wear test currently underway at JPL.
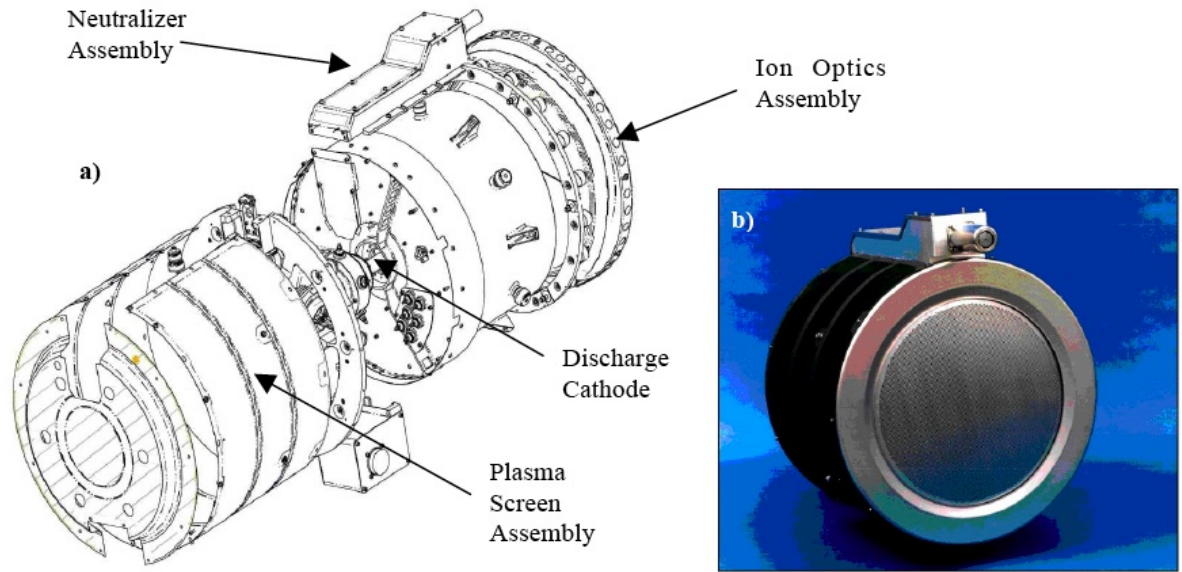
Figure 1. Exploded view and photograph of the XIPS 25 cm ion thruster.[2]

III. Status of The On-Going Cathode Wear Test

The objective of the XIPS discharge cathode wear test is to identify any unknown failure modes and characterize the drivers of known failure processes in extended operation at the maximum power point and at a number of throttled conditions. The first operating point corresponds to the full power point tested for 2680 hours in the L3 wear test. Because deep space applications will require more operating time at full power than the orbit-raising applications, a total of 5666 hours were accumulated at the full power point in this test. The second operating point was chosen to correspond to a thruster throttle level of 2.75 kWe, which is 2/3 of the full power and lies between the low and high power points explored in the L3 wear test. A total of 5414 hours of operation at this new condition have been accumulated in a second test segment that is about to be completed. This will be followed by extended testing at a condition representing the lowest power level of interest for planetary missions, which will be chosen on the basis of ongoing trajectory analyses for candidate applications.

III.A. Test Article

A complete discharge cathode assembly that was fabricated using all of the flight component manufacturing and inspection processes was provided by L-3 ETI for this wear test. The brazed and welded assembly consists of the impregnated tungsten insert, the cathode tube and orifice plate, keeper electrode, cathode-to-keeper insulator, and the rear housing with the electrical terminals and gas connector, as shown in Fig. (2).

III.B. Wear Test Facility

The cathode wear test is being conducted in a 1 m diameter by 2 m long vacuum facility which is pumped by two 25 cm diameter cryopumps. Pressure is monitored with an ion gauge calibrated with nitrogen gas. The base pressure is typically 1.3×10^{-4} Pa (1×10^{-6} Torr) and the xenon pressure during cathode operation ranges from $2.7 - 4.0 \times 10^{-3}$ Pa ($2 - 3 \times 10^{-5}$ Torr), assuming a gas correction factor for xenon compared to nitrogen of 2.8.

We have found that cathode performance, measured in terms of discharge and keeper voltage and ion production efficiency, is very sensitive to the anode configuration.[13,14] Typical cathode diode tests with a
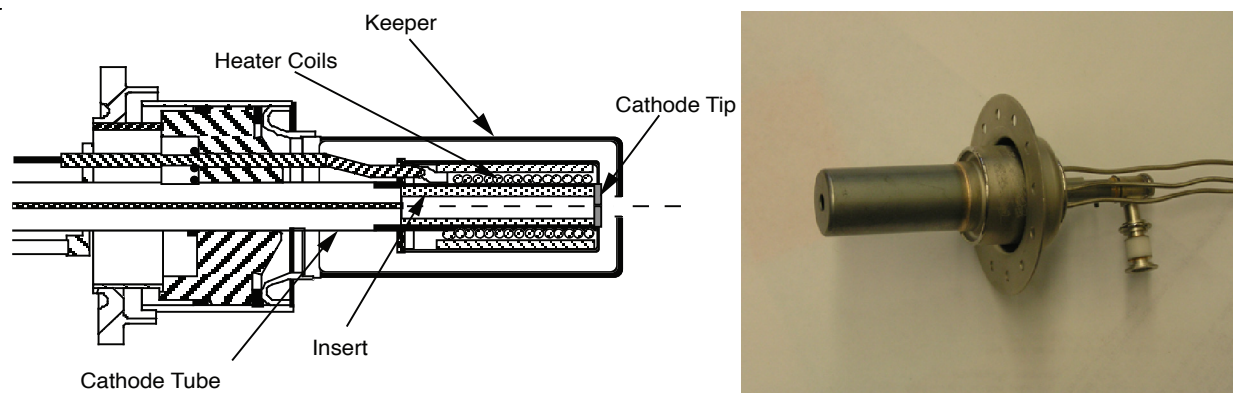
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Figure 2. Schematic and photograph of the XIPS discharge cathode assembly.[12]

keeper electrode only or triode tests with a flat plate anode do not produce results that are representative of performance in ion engine discharge chambers. The discharge chamber shown in Fig. (3) and schematically in Fig. (4) was designed specifically to simulate the environment of a ring cusp ion engine. It incorporates a water-cooled copper anode with cylindrical and conical sections, three rings of SmCo magnets and a water-cooled solenoid around the cathode. Magnetic field strengths of 1500 to 1900 G in the cusps, 120-125 G at the cathode orifice and 45 G closed contours between cusps provide good plasma confinement and stable operation. A flat molybdenum plate occupies the downstream end of the discharge chamber instead of the ion extraction grids found in an actual engine. The gap between the plate and the anode is set to provide a certain neutral loss rate.
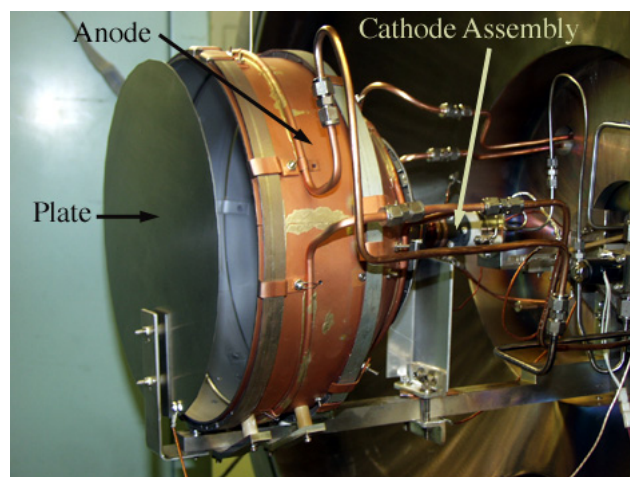

Figure 3. Photograph of the discharge chamber configuration used for cathode performance testing.

The xenon flow system and electrical configuration are shown schematically in Fig. (4). Ultra-high purity xenon is used as the cathode expellant. The flow rate is measured with a thermal mass flow meter and controlled with a closed-loop controller and solenoid valve. The valve is mounted in the vacuum chamber so that all external feed lines are above atmospheric pressure to eliminate the possibility of air leaks into the flow system. Main flow is introduced into the discharge chamber through a manifold located in the center of the cylindrical section and controlled with a separate flow controller. The meters were calibrated by measuring the rate of pressure rise in a known volume, yielding flow rate measurements with an uncertainty of less than 2%.

Heater, keeper and discharge power are provided by commercial power supplies, with the common returns grounded to the vacuum tank. The cathode is also grounded to the chamber through the mounting structure. Currents and voltages are measured to within 1% by the data system using calibrated shunts and voltage dividers.

The molybdenum plate at the downstream end of the discharge chamber can be biased with respect to the cathode ground. If the bias voltage is sufficiently negative to repel all electrons, typically less than -14 V, the ion current to the plate can be measured. However, it is generally operated at a less negative voltage than this to minimize sputtering. After 1312 hours of operation a 12.5 mm diameter carbon disk probe was added at the center of the molybdenum plate. The probe is biased -20V with respect to the cathode to collect the ion current, which is used as a measure of the discharge ion production rate.

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III.C.   Cathode Performance in the 5666 Hour High Power Test Segment

A time history of cathode operation in the wear test is shown in Table (2) and the discharge current and voltage are plotted in Fig. (5). The cathode was first subjected to a 238 hour burn-in test at the maximum current level of 21 A, then throttled down to the nominal value of 18 A for the XIPS high power operating point.

Over the next 330 hours a number of discharge operating parameters were changed to more accurately reproduce the conditions in a XIPS thruster. The primary objective was to match the 25 V discharge voltage at which the thruster runs in the full power mode. The cathode flow rate was set at the nominal value and the main flow rate, the current in the solenoid surrounding the cathode and the bias voltage on the plate at the downstream

Figure 4. Schematic of the discharge chamber, flow and electrical systems used in performance measurements.

end of the discharge chamber were varied to produce a discharge voltage of 25 V. Changes in the main flow rate alter the neutral density in the discharge chamber while changes in the magnetic field strength and plate bias affect the primary electron loss, all of which impact the discharge voltage.

After 570 hours of total operation, the magnet current was increased to produce a field strength of 120-125 G at the cathode, which better simulates the thruster environment. The other independent parameters were adjusted to maintain a discharge voltage of 25 V. Over the next 730 hours the discharge voltage dropped by about 0.9 V, as shown in Fig. (5). This behavior is not uncommon in cathode wear tests that employ constant discharge current,[15–17] and probably reflects improvements in the cathode emitter surface state.
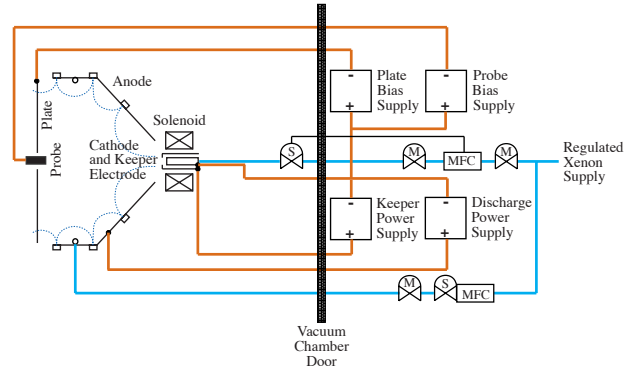
Table 2. Test Timeline with Operating Points

Time (Hrs)	Discharge Current (A)	Cathode Flow (sccm)	Main Flow (sccm)	Solenoid Current (A)	Plate Bias Voltage (V)	Control Mode	Comments
Test Segment 1: High Power Operating Point							
0-238	21	2.8	1.6	10	-10.0	Constant J_d	Burn-in at Maximum J_d
238-313	18	2.8	0.4	13	-7.0	Constant J_d	Adjustments to Best
313-570	18	2.8	0.4	15	-7.0	Constant J_d	Match Thruster
570-1312	18	2.8	0	20	-7.5	Constant J_d	Conditions at High Power
1312							Opened To Inspect and Modify for Closed-Loop Control
1312-1484	18	2.8	1.0	20	-5.0	Constant J_d	Changes to Control Mode
1484-1792	18.3	2.8	0.8	20	-4.0	Constant J_{pl}	at the High Power
1792-5666	18.3-20.6	2.8	0.8	20	-4.0	Constant J_{pr}	Point
5666							Opened To Inspect
Test Segment 2: Intermediate Power Operating Point							
5666-5729	20.7	2.8	0.8	20	-4.0	Constant J_{pr}	High Power Point Check
5729-6759	10.36	1.9	0	20	-4.0	Constant J_d	Intermediate Power Point
6759-7909	10.36-10.84	1.9	0	20	-4.0	Constant J_{pr}	Intermediate Power Point
7909							Opened To Inspect
7909-11080	10.36-10.7	1.9	0	20	-4.0	Constant J_{pr}	Intermediate Power Point

However, we were concerned that the discharge voltage might drop to a level unrepresentative of discharge chamber operation. After 1312 hours of operation the decision was made to reconfigure the setup in order to simulate beam current control in a thruster. The cathode was purged with research grade argon at a flow
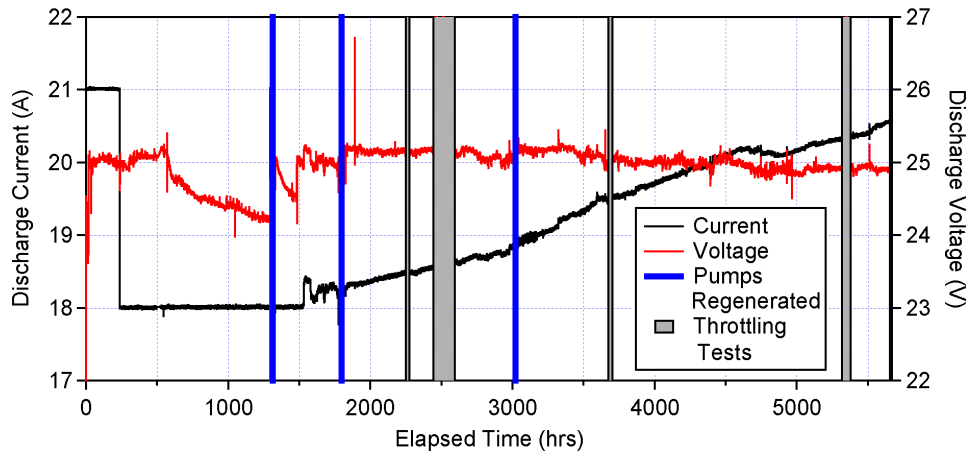
Figure 5. Discharge voltage and current as a function of test time during the high power test segment.

rate greater than 20 sccm during venting and while the setup was exposed to atmosphere. The molybdenum plate was modified to accommodate the probe and the plate-to-anode gap was increased from 0.4 to 1 cm. This increased the neutral loss by a factor of 2.5, allowing the use of a non-zero main flow.

After the modification, regeneration of the cryopumps and re-conditioning of the cathode, the discharge was operated in several different control modes for about 500 hours. In initial operation with a constant discharge current of 18 A for 170 hours the discharge voltage continued to drop from the initial set point of 25 V. For the next 300 hours the discharge current was varied to maintain a constant current to the molybdenum plate, which was biased only -4.0 V with respect to the cathode to prevent excessive sputtering. At this bias voltage the plate collects both electrons and ions with a net positive current, which may therefore be sensitive to changes in electron temperature. As shown in Fig. (5), the discharge voltage remained at about 25 V and the discharge current was approximately constant at 18.3 A. The probe current was ultimately selected as the control parameter and was used for the remainder of the test. It is biased -20 V to repel all electrons, making it less sensitive to changes in electron temperature, and because it is made of more erosion-resistant carbon and has a smaller area it generates less sputtered material than the plate would at -20 V.

As Fig. (6) shows, the control algorithm maintained a constant probe current for the remainder of the first test segment. The slightly larger amplitude variations in probe current from 3000 to about 3150 hours were due to a larger deadband in the control algorithm. Assuming that the probe current is an accurate reflection of the ion production rate in the discharge chamber, the ion production rate was constant during this portion of the test. Figure (5) reveals that the discharge power had to increase to maintain the ion production rate, however. Although the discharge voltage has not varied significantly, the discharge current has increased from 18 A to 20.6 A, which represents an 11% increase in ion production cost, defined as the discharge power required to produce a given ion current to the probe. The plate current did not vary significantly over the course of the test.

Figure (7) displays the cathode keeper voltage and current. The current was maintained at 1 A for the entire test segment. The keeper voltage varied from 6-7 V initially, while the nominal test conditions were being adjusted, and was constant at 7.5 V after 1312 hours. This value is at the low end of the allowable range for flight XIPS thrusters, most of which have keeper voltages ranging from 8 to 9 V.

The chamber pressure as a function of elapsed time is plotted in Fig. (8). The cathode flow rate was constant at 2.8 sccm, so the variations in chamber pressure are due to changes in the main flow rate, pumping efficiency and ambient temperature. The high initial pressure is attributable to the high main flow rate at the 21 A current condition. Subsequent drops are due to decreases in the main flow rate. After the first regeneration, the main flow was increased from zero to 1 sccm, increasing the pressure. The second regeneration evidently resulted in improved pumping efficiency. The trend upward in pressure after this point appears to be due to higher ambient temperatures during the summer. A power outage at 3020 hours resulted in a facility shutdown and the third regeneration.
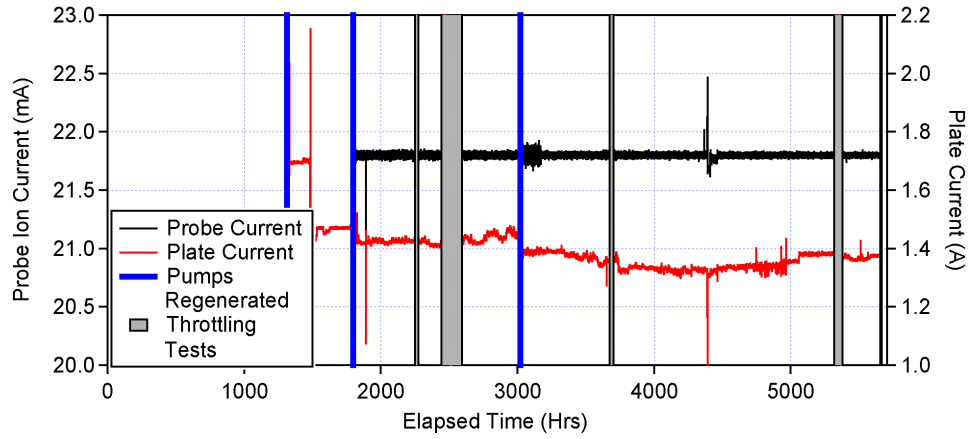
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Figure 6. Variation in current collected by the plate and the probe during the high power test segment.
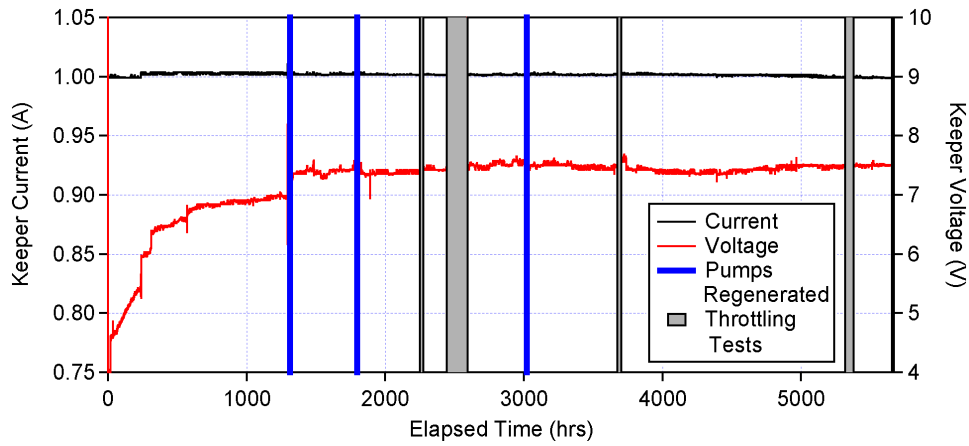

Figure 7. Keeper electrode voltage and current as a function of test time during the high power test segment.
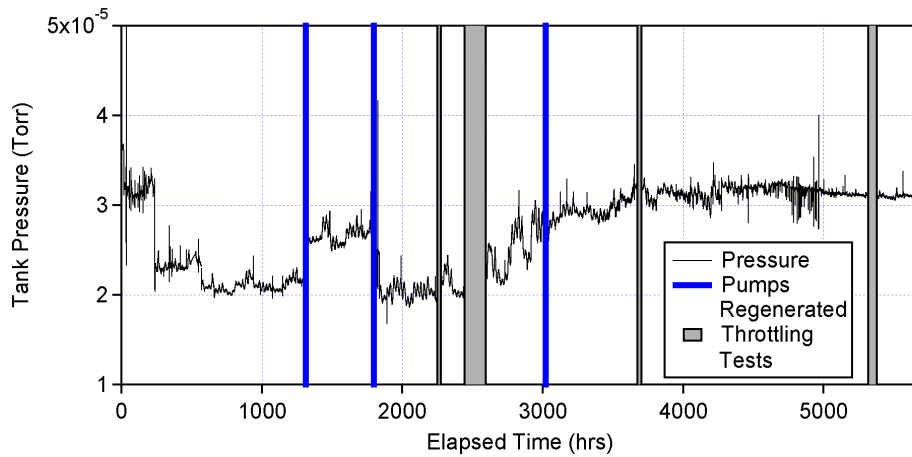

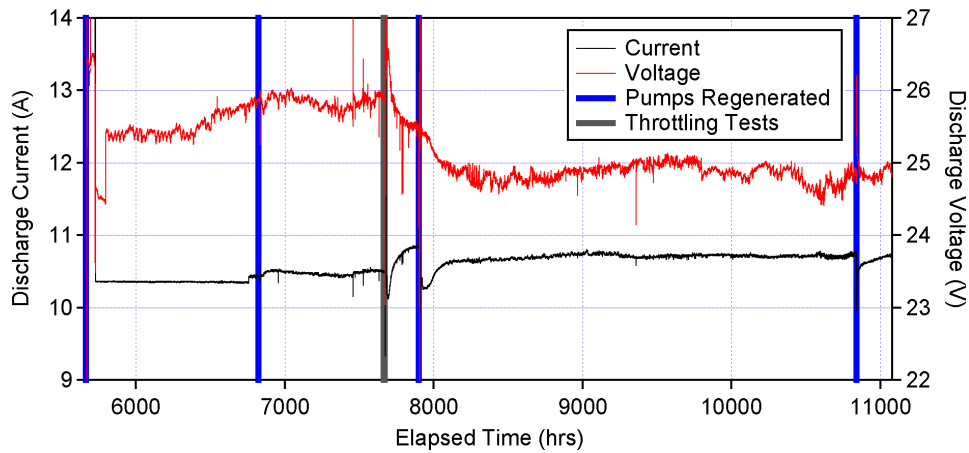**Figure 8. Vacuum chamber pressure over the course of the high power test segment.**

Figure 9. Discharge voltage and current as a function of test time during the intermediate power test segment.

The 5666 hours accumulated at this operating point is 1.88 times the 3000 hours of high power thruster operating time anticipated for typical planetary missions. The electrical data give no indication of degradation in emitter condition, and the changes in cathode performance are not atypical for thruster operation. For example, the increase in current required to maintain a constant ion production rate is similar in magnitude and occurs over a similar time scale as that observed in the 8200 hour wear test of the 30 cm NSTAR thruster.[16] Inspection of the cathode assembly after this test segment revealed thinning of the keeper orifice plate and enlargement of the keeper orifice, described in more detail in section III.E, but no component damage that threatened cathode operation at this point. The test was then resumed for a second segment designed to demonstrate extended operation at an intermediate current level.

III.D.   Cathode Performance in the Ongoing Intermediate Power Test Segment

The timeline of the second test segment is summarized in Table (2). The cathode was first operated for 63 hours at the high power point with the same setpoints used in the previous test segment to check repeatability. The keeper voltage and the plate current were within a few percent of the previous values, but the discharge voltage was 1.5 V higher. This difference was attributed to a lower chamber pressure and small changes in the plate-to-anode gap that occurred in disassembly and reassembly during the cathode inspection. Both of these changes affect neutral density in the discharge chamber and therefore the discharge voltage.

The cathode was then throttled down to 10.36 A, which is the discharge current setpoint for a thruster power level of 2.76 kWe. This point was chosen to provide more operating experience at a power level intermediate between the low power mode tested for 13400 hours in the L3 thruster wear test and the full power point tested for 2680 hours at L3 and in the first segment of this test. The cathode was operated with a constant discharge current for 1030 hours. It was then placed under closed loop control, with discharge current varying to maintain a constant probe current, and has accumulated 5414 hours at the intermediate power point and a total of 11080 hours of operation.

As shown in Fig. (9), the discharge voltage varied between 25.4 and 25.8 V over the first 1030 hours in constant current mode. The discharge current and voltage were both initially stable at 10.5 A and 25.8 V in probe current control mode. After throttling tests at 7670 hours, the discharge voltage initially rose to 26.5 V and then dropped to 25.5 V as the discharge current dropped to 10.1 A and then rose to 10.85 A. At 7909 hours the chamber was opened to inspect the cathode assembly for signs of erosion that might explain these transients. No major changes in the keeper or cathode geometry were found, as discussed in section III.E. We do not currently understand what caused this brief trend in voltage and current. After the test was restarted, the current and voltage rapidly reached stable values of about 10.7 A and 24.9 V. Comparison of the discharge voltage and chamber pressure in Fig. (10) shows that much of the voltage variation is correlated with the pressure, indicating that it is due to small changes in neutral density in the discharge chamber.

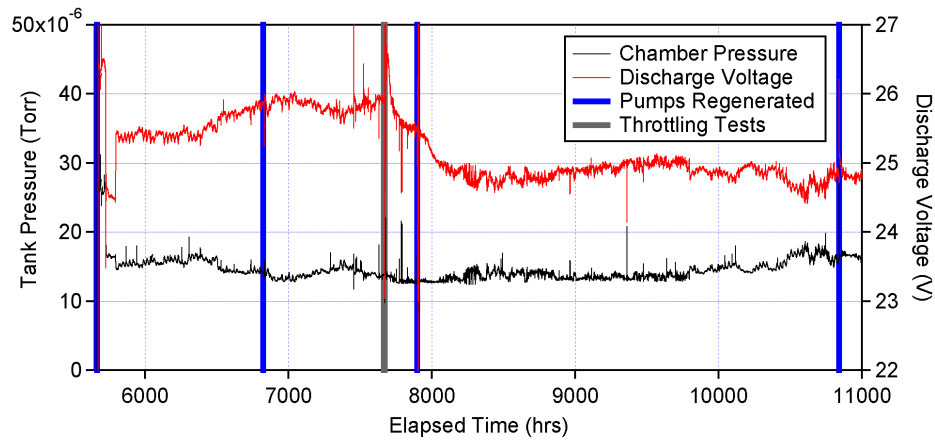American Institute of Aeronautics and Astronautics

Figure 10. Variation of vacuum chamber pressure and discharge voltage during the intermediate power test segment.

The cathode keeper current and voltage are displayed in Fig. (11). The voltage has varied between 9.5 and 10 V over the course of the second test segment. Most of the variation is correlated with changes in chamber pressure, except for a drop in voltage between 7670 and 7909 hours which follows the trends in the discharge voltage.

Figure (12) demonstrates that the control algorithm has maintained a constant probe current, and therefore, presumably, a constant ion production rate. The plate current has also been relatively constant at about 0.5 A. Because the discharge power has been nearly constant at 267 W, the ion production cost did not change significantly at this operating point.

This test segment has demonstrated operation at the intermediate power level for over 5414 hours with little erosion and no major changes in performance. The final test segment will demonstrate operation at a low throttle point.
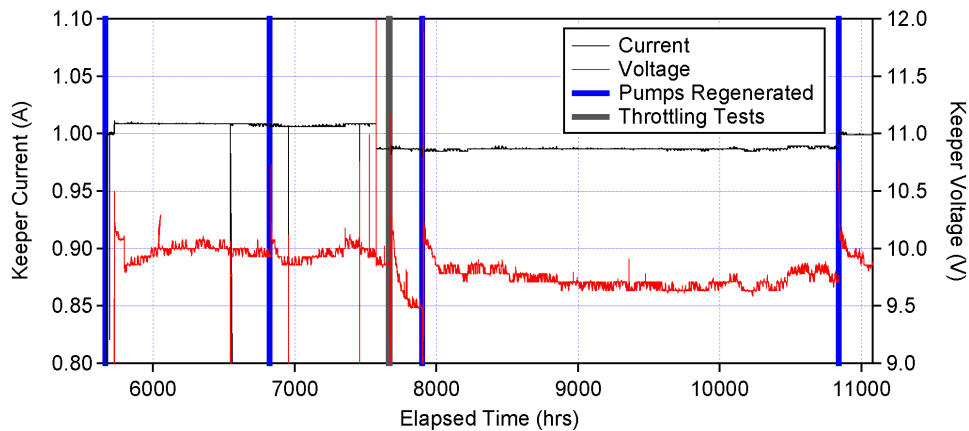

Figure 11. Keeper electrode voltage and current as a function of test time during the intermediate power test segment.

III.E.   Cathode Assembly Inspections

The modification to the test setup at 1312 hours provided the opportunity to inspect the cathode and test fixture, which revealed no signs of damage other than a slight texturing of the keeper due to ion bombardment, as shown in Fig. (13). The assembly was inspected again after completion of the first test segment at 5666 hours. The photographs in Fig. (13) show that the keeper orifice diameter increased due to sputter erosion. Measurements of the orifice diameter using pin probes with an uncertainty of ± 25 μm showed that the diameter increased to 1.28 times the original diameter. A precision dial indicator was used to measure the

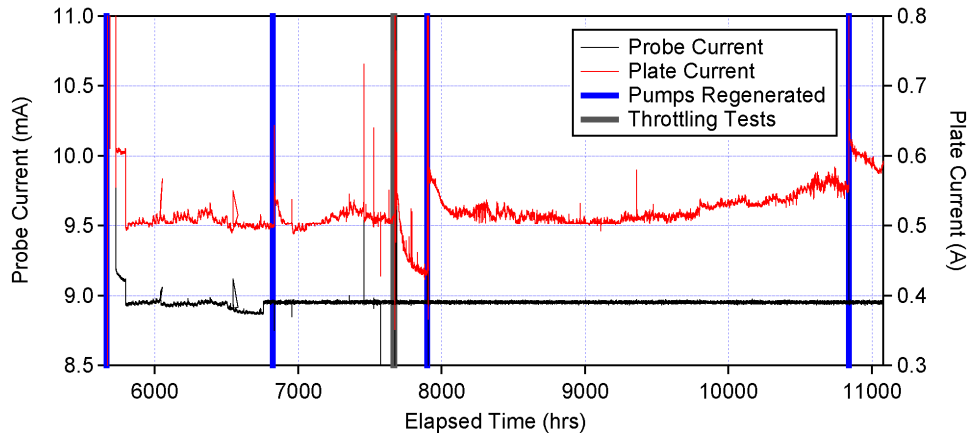American Institute of Aeronautics and Astronautics

Figure 12. **Variation in current collected by the plate and the probe during the intermediate power test segment.**

profile of the keeper face with an uncertainty of ± 25 μm, and the results plotted in Fig. (14) indicate that the orifice plate thickness has decreased by about 50% at the orifice. The cathode orifice diameter did not change, but the photographs in Fig. (13-c) show that the edge of the orifice chamfer was not as distinct as in the earlier photographs, indicating some rounding of the sharp edge due to erosion. The keeper erosion may have contributed to the performance changes noted in this test segment, but has otherwise not adversely affected cathode function.

The inspection at 7909 hours, after 2180 hours at the throttled operating condition, showed that the keeper orifice diameter increased by only about 4% (i.e. a diameter 1.33 times that at the beginning of the test). No additional thinning of the orifice plate could be measured to within the resolution of the gauge (about ± 25 μm). The photographs in Fig. (13-d) show no major changes in cathode orifice plate condition, and pin probe measurements indicated that the cathode orifice diameter did not change. The intermediate power point is evidently a more benign operating condition.

IV.   Conclusions

The objective of this test was to reveal any new failure modes, measure component wear to aid in developing physics-based models of the wear mechanisms and characterize any changes in performance. A total of over 11080 hours have been accumulated to date in two test segments corresponding to 5666 hours at the full power engine operating point of 4.2 kWe and 5414 hours corresponding to operation at 2.76 kWe. No unexpected failure modes or wear processes have been observed, and the cathode continues to run well. Cathode keeper erosion occurred at the full power point, confirming that the discharge cathode is a critical component in determining the ultimate thruster service life capability. Recent modeling and experimental efforts have yielded a better understanding of the physical mechanism driving keeper wear. Under certain operating conditions, high frequency fluctuations in the plasma potential are observed near the face of the keeper.[18] Estimates of the keeper orifice plate erosion due to ions accelerated by the fluctuating potentials are consistent with the pattern and magnitude of erosion we have observed.[19] Further experiments are planned to map out the magnitude and variability of potential oscillations over the XIPS throttle range to assess the risk at throttled conditions. The operating time accumulated at the full power operating point was over 1.8 times that expected for typical planetary missions, and the observed wear rate appears to be tolerable. However, to minimize the risk to the cathode due to keeper erosion, a tantalum keeper will be used in thrusters built for planetary missions. This approach was also employed in the NSTAR thrusters built for the Dawn mission,[20] and the reduced sputter yield of tantalum compared to molybdenum essentially eliminates keeper erosion as a critical failure mode.[19]

The 11% increase in ion production cost implied by the rise in discharge current during this segment is similar to that observed in the NSTAR ion thruster and is not a significant performance loss. At the intermediate power point there were no changes in performance and negligible erosion. At this point the XIPS discharge

a. Beginning of Test

b. 1312 Hours

c. 5666 Hours

d. 7909 Hours

Figure 13. Photograph of the discharge cathode and keeper assembly after 1320 hours of operation.

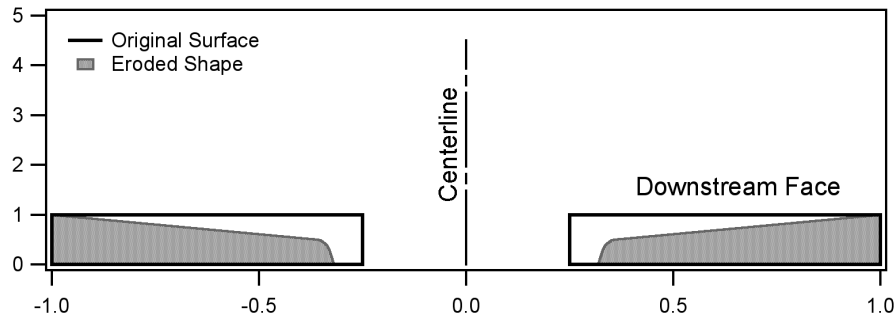American Institute of Aeronautics and Astronautics

Figure 14. Cathode keeper erosion profile measured after 5666 hours of operation at full power.

cathode appears to have adequate life for deep space applications, particularly with the use of a tantalum keeper to reduce orifice plate erosion. The cathode will be operated for an extended period at a low power operating point in the final segment of the test to identify any unexpected wear phenomena at the extreme end of the throttle range.

V.   Acknowledgements

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